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CONVAIR DIVISION OF GENERAL DYNAMICS CORPORATION

ZERO-G REPORT

LH_2 FILM BOILING

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SUMMARY

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Drop tests and aircraft tests were conducted to study the zero-g film boiling of liquid hydrogen. Metal films deposited on microscope slides were electrically heated in LH_2. In the drop tests, the threshold of the transition to film boiling occurred between 12,500 and 18,000 BTU/HrFt^2 with a temperature rise near 11 Fahrenheit degrees. The aircraft tests roughly substantiated this up to two seconds of zero-g. Beyond two seconds the data indicated a slight decrease in both the temperature and heat flux required to initiate the transition to film boiling. The motion picture results from heated-plate drop tests at well above the threshold heat rates showed that one large bubble was formed almost immediately. Figure 5 shows a photo enlarged from the movie.

Author

In another series of tests, the liquid was discharged from a tube at Centaur settling velocities against relatively warm surfaces (100 - 300°R). See Figures 6 and 7. It was not repelled or appreciably agitated. Figure 8 shows the quenching curve (i.e., heat flux versus temperature difference) for such impingement.

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LH_2 FILM BOILING

1.0 INTRODUCTION:

1.1 During the coast or orbital phase of a typical Centaur Flight, the liquid hydrogen will be in a zero gravity field. Under such conditions the liquid would wet the walls of an unheated tank, leaving the ullage space in the center. However, it is conceivable that, due to mechanical or thermal effects, portions of the Centaur tank walls will not be wetted. Upon the firing of the settling rockets the liquid hydrogen could be brought into contact with a relatively warm surface as the vehicle gains momentum. It was considered possible that the resultant film boiling would repel the liquid from such a surface, thus adding to the settling problem. In order to investigate general liquid behavior and film boiling heat transfer during reduced and zero gravity, tests were conducted in a U.S.A.F. KC-135 aircraft and with laboratory apparatus. The KC-135 was capable of attaining several seconds of zero-g while the drop tests were limited to one second of zero-g. Details concerning the flight tests may be found in (Reference A).

2.0 TEST OBJECTIVES:

2.1 The test objectives were as follows:

1) The determination of the threshold of the transition to film boiling during zero-g.

2) The verification of the existence of the time dependency of film boiling in zero-g.

3) The determination of the hydrogen (liquid and vapor) behavior during zero-g when a surface is heated to temperatures where film boiling occurs.

4) The determination of the zero-g behavior of liquid hydrogen when brought into contact with a relatively warm surface.

5) The determination of the transient film-boiling heat transfer when the liquid is impinged against a relatively warm surface at the velocity expected during the initial liquid to surface contact in the Centaur.

2.2 Note that for objective (4) a fixed quantity of heat (determined by the specimen temperature, mass, and specific heat) was supplied to the LH_2, while in (3) a fixed rate of heat (and hence a dependent temperature) was used.

3.0 TEST APPARATUS:

3.1 The drop test apparatus and the wall boiling flight test capsule, described in Reference B, were used to study the threshold of transition to film boiling and its time dependency.

3.2 This drop test apparatus was also used to determine the liquid and vapor behavior during zero-g when a surface was suddenly heated to temperatures where film boiling would occur. This test specimen was a piece of 301 (extra full hard) stainless steel, 0.010" thick with a heating surface of 2.0 square inches. It was insulated on the under side. The power supply was modified in order to supply heating power to this low resistance specimen (.04 ohms). The film boiling was photographed by a motion picture camera. No temperatures were measured.

3.3 The tests for determining the liquid behavior upon contact with a relatively warm surface and the heat transfer during the contact were conducted with the relatively simple warm plate impingement capsule, Figure 1. This capsule consisted of a tubular frame which housed the following components:

1) the 4.3 liter dewar that contained the LH_2, the percolator, and the heated specimen;

2) the motion picture camera and lights; and

3) the timing lights.

(Continued)

3.0 TEST APPARATUS: (Cont)

3.3 (Cont)

The capsule was connected by a trailing wire to the power supply and Sanborn recorder which were solidly attached to the aircraft. The effect of the trailing wire on the capsule during zero-g was considered negligible for this test. The liquid hydrogen was impinged against the specimen by the percolator, Figure 2. When the resistance heating element within the reservoir of the percolator was energized a hydrogen gas bubble was formed. The expansion of this bubble forced the LH_2 out of the reservoir, through the connecting tube, and against the plate specimen at velocities near 1/2 ft/sec. At the end of a zero-g trajectory, small holes located on the top and bottom of the reservoir permitted LH_2 to refill the reservoir and allow the residual gas to escape. The specimen under test was located 1/4 inch above the percolator tube outlet normal to the impinging stream of LH_2. Both a thin stainless steel specimen and a copper specimen were used to obtain the required data. The stainless steel specimen was used to study liquid behavior while the copper specimen was used to establish the transient film boiling heat transfer during the impingement. The stainless steel specimen, Figure 3, consisted of a piece of 301 (extra full hard) stainless steel, 0.010" thick and 2 inches in diameter. The material and gage of the specimen where chosen to match the representative tank wall and bulkhead materials in the Centaur Vehicle. The plate was heated by a resistance heating element and its temperature was measured by copper-constantan thermocouples. The copper plate specimen, Figure 4, consisted of 1.0 inch diameter plate 3/16 inch thick. To reduce edge effects, the 1.0 inch plate was insulated around its edges with an epoxy resin and surrounded with a two-inch diameter guard ring of copper. The copper plate and guard ring were also heated from the rear by a resistance heating element.

4.0 **PROCEDURE:**

4.1 The procedure used with the wall boiling capsule and the drop test apparatus was the same as that described in Reference B. A manual "panic switch" was added to the wall boiling capsule to cut off power if a breakaway temperature rise occurred. Motion picture coverage of the action within the dewar was allthat was required for investigating the liquid and vapor behavior in film boiling (Test Objective 3).

4.2 Prior to conducting the flight tests with the warm-plate impingement capsule, the following minimum data requirements were established for each type of specimen: Two good trajectories at temperatures of 300, 200, and 100°R. The liquid velocity in each case was to be about 1/2 ft/sec.

The initial temperature of the plates was chosen to cover the values that would be expected to occur during a Centaur Flight. The velocity chosen was one which would be typical during the initial liquid to surface contact.

A typical test sequence was as follows:

1) The Sanborn recorder was turned on, and heat was supplied to the plate just prior to entering the trajectory.

2) Upon entering the trajectory, the plate heat was turned off, and the camera and lights were turned on.

3) At the pilot's command, the capsule was released, and the percolator was energized.

4) At the end of the maneuver, the capsule was secured and prepared for the next trajectory.

5.0 RESULTS AND DISCUSSION:

5.1 The recorded data (open vent only) from the one second drop tests indicated that the transition to film boiling occurred at heat fluxes between 12,500 and 18,000 BTU/Hr Ft^2 with a temperature rise near 11 Fahrenheit degrees. The aircraft data (open and closed vent) roughly substantiated this up to two seconds of zero-g. Beyond 2 seconds, the data indicated a slight decrease in the temperature required to initiate the transition to film boiling. See Figure 9. A similar, but even less well defined trend in the heat flux required to initiate film boiling is presented in Figure 10. (Note that the reference temperature of the closed vent results was taken as the saturation temperature at the dewar vapor pressure at the instant of the measurement. No such correction was devised for the heat flux data).

A review of the motion picture results was undertaken to determine (if possible) the reason for this phenomenon. The results of the review were as follows:

1) During the aircraft open-vent tests a large vapor bubble (possibly part of the ullage space) was seen in the vicinity of the heated specimen. This bubble could have caused the breakaway rise in temperature by enveloping the plate. The photos were very poor.

2) Photos of the closed vent trajectories revealed that the growth of the single vapor bubble became restricted by a baffle[1] just prior to the increase in temperature. After the bubble entrapment, vapor was seen in the form of a bubble on the glass side of the specimen, indicating a decrease in heat transfer from the metal face (and an increased temperature). This brought to mind the possibility of a geometry effect on heat transfer. The magnitude of this effect could be determined if a trajectory was flown without the effect of the baffle; and this was done. The data thus obtained were even lower than the baffle data. This would tend to cast doubt upon the geometry effect.

(1) See Reference A.

5.0 RESULTS AND DISCUSSION: (Cont)

5.1 (Cont)

In a farther attempt to gain a better understanding of the problem, data was examined from the first four Aerobee tests conducted by the Lewis Research Center. The burn out locations and times reported do not seem to be thermally consistent without postulating that the geometric or mechanical conditions affect the thermal picture.

5.2 The time dependency of film boiling in zero-g is still unresolved. Our data is presented in Figures 8 and 9 for the reader to evaluate for himself. Several speculations on the cause of the time dependency have been put forth by those who have worked closely on this project. We have not, however, been able to reduce any of these speculations to verifiable theory.

5.3 The motion picture results from the film boiling drop tests revealed that one large bubble formed almost immediately over the heated plate. Figure 5 is a still photograph enlarged from the 16 MM film. To allow for the poor resolution of the enlargement, a sketch is presented to show more clearly the bubble formation.

5.4 The motion picture results obtained from the warm plate impingement tests revealed the liquid hydrogen was not repelled or appreciably agitated when it impinged against a relatively warm surface (with a limited heat content). In order to show that no rejection of the liquid occurs, a series of still photographs from two typical trajectories are presented in Figures 6 and 7. Again sketches are included.

5.0 RESULTS AND DISCUSSION: (Cont)

5.5 The film boiling heat transfer during the impingement against the copper plate was determined in accordance with the following assumptions:

1) Since the plate was guarded, the only temperature gradient present was normal to the exposed surface.

2) Since the thermal conductivity of copper was high and plate was thin, the temperature gradient through the plate was assumed negligible.

In view of these assumptions the rate of heat loss per unit area (heat flux) is:

$$q = \frac{M\,C}{A}\,\frac{dT}{dt}$$

Where:

q = heat flux
M = the mass of the plate
C = the specific heat of copper
A = the surface area
$\frac{dT}{dt}$ = the rate of change temperature with time (Sanborn recording)

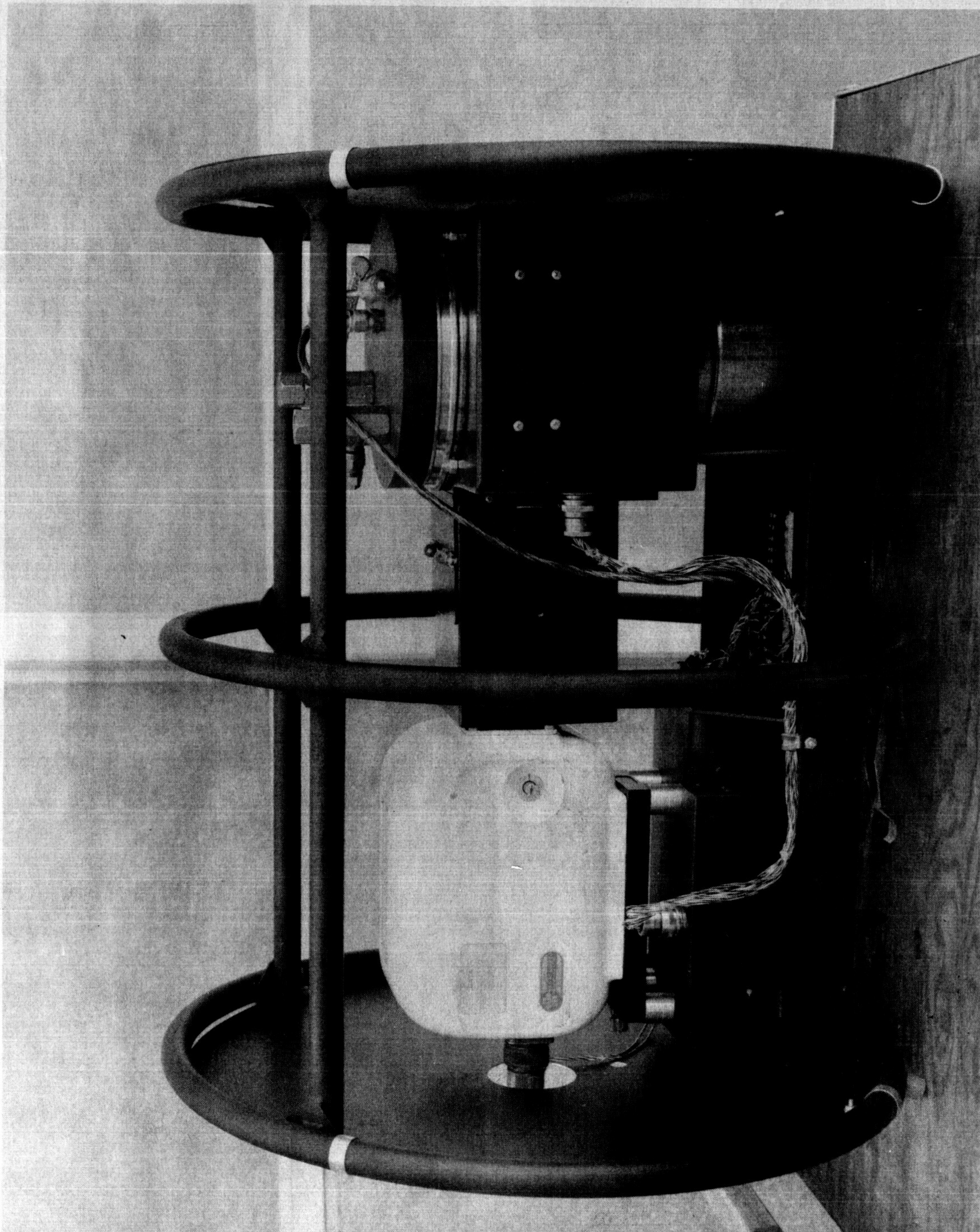
Two trajectories were flown without the liquid being impinged upon the stainless steel plate. From this, the heat flux to hydrogen gas was obtained. These values were subtracted from the heat loss rate during LH_2 impingement to allow for the heat lost from the back of the plate to the gas. Figure 8 presents the results. Also the zero-g nucleate-boiling heat-transfer data from Reference B is included on Figure 8 for comparison, even though it is not strictly comparable with the impingement heat transfer data. The nucleate boiling test started with liquid completely surrounding the plate. The gas produced by the boiling built-up as a bubble next to the plate -- i.e., the general liquid mass was held away from the plate. In contrast, the impingement test started with gas surrounding the plate, and the boil-off could easily escape into the ullage space with the liquid remaining close to the plate.

REFERENCES

A) Hansen, Perkins; Zero-G Report: Flight Test Development; Test Laboratories Report 55D 859-4; March 1962.

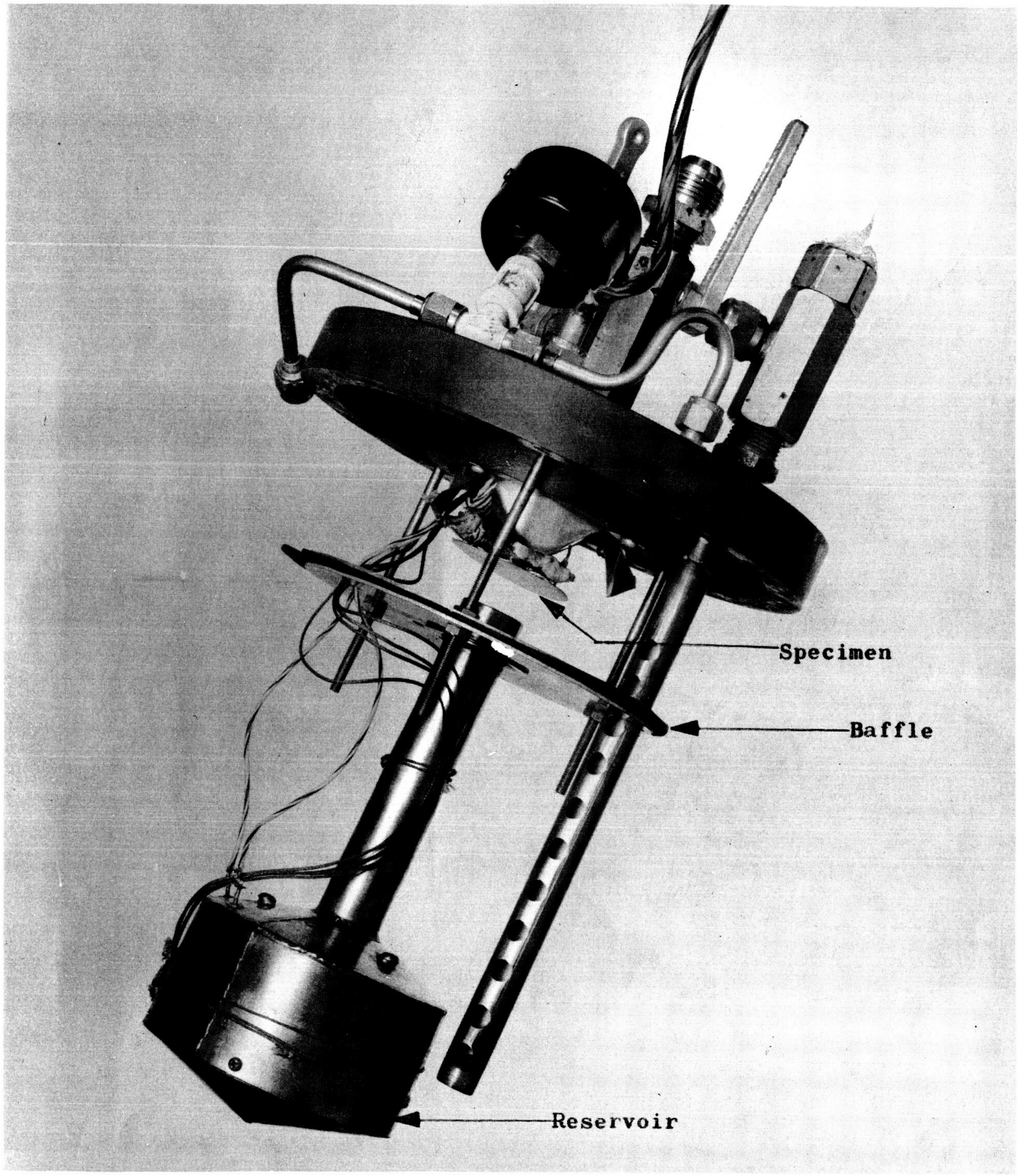
B) O'Hanlon, T.W.; Zero-G Report: LH_2 Nucleate Boiling; Test Laboratories Report 55D 859-1; January 1962.

C) Tuck, G.; Zero-G Report: LH_2 Boiling Threshold; Test Laboratories Report 55D 859-3; March 1962.



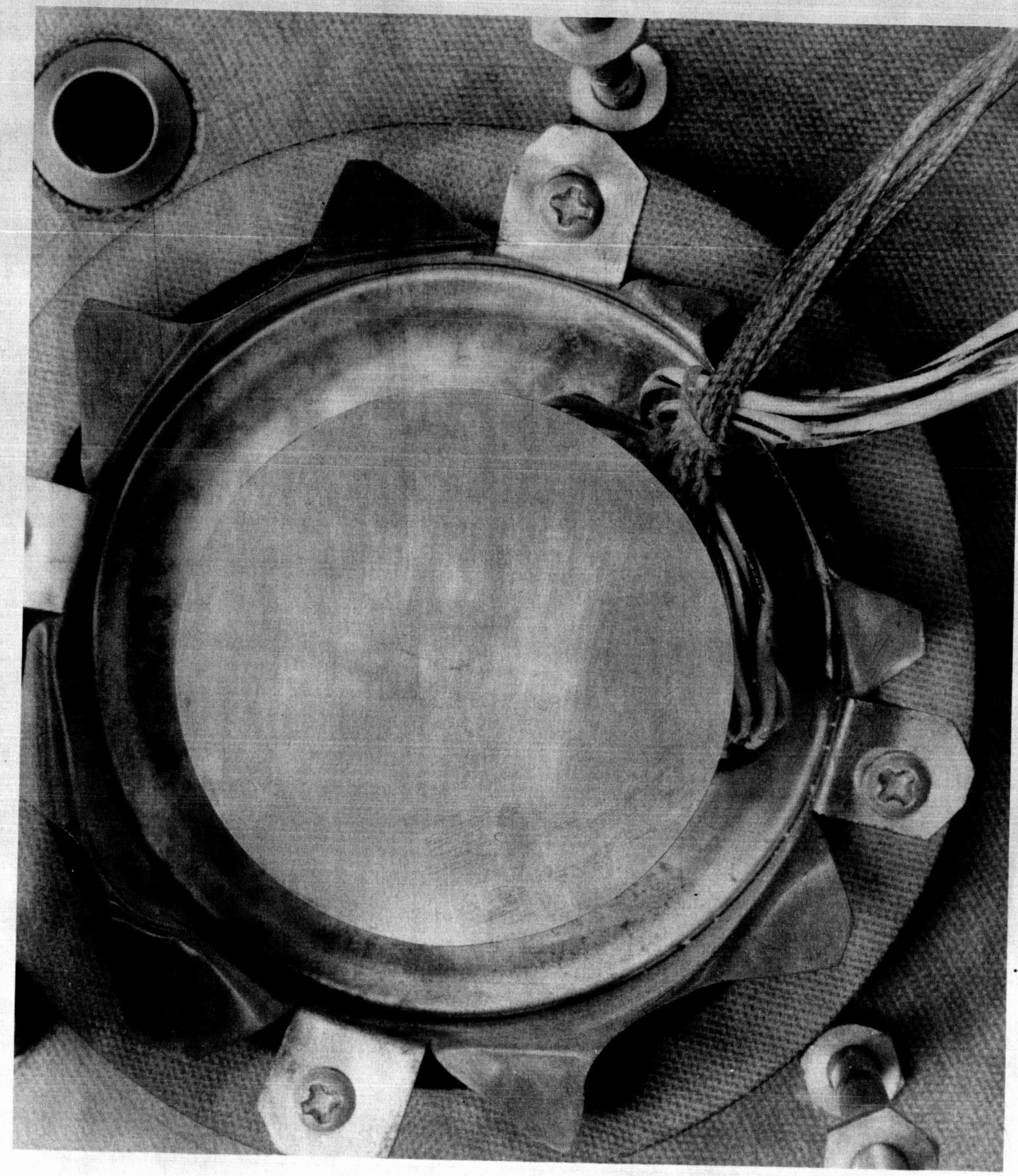
WARM PLATE IMPINGEMENT CAPSULE

Figure 1



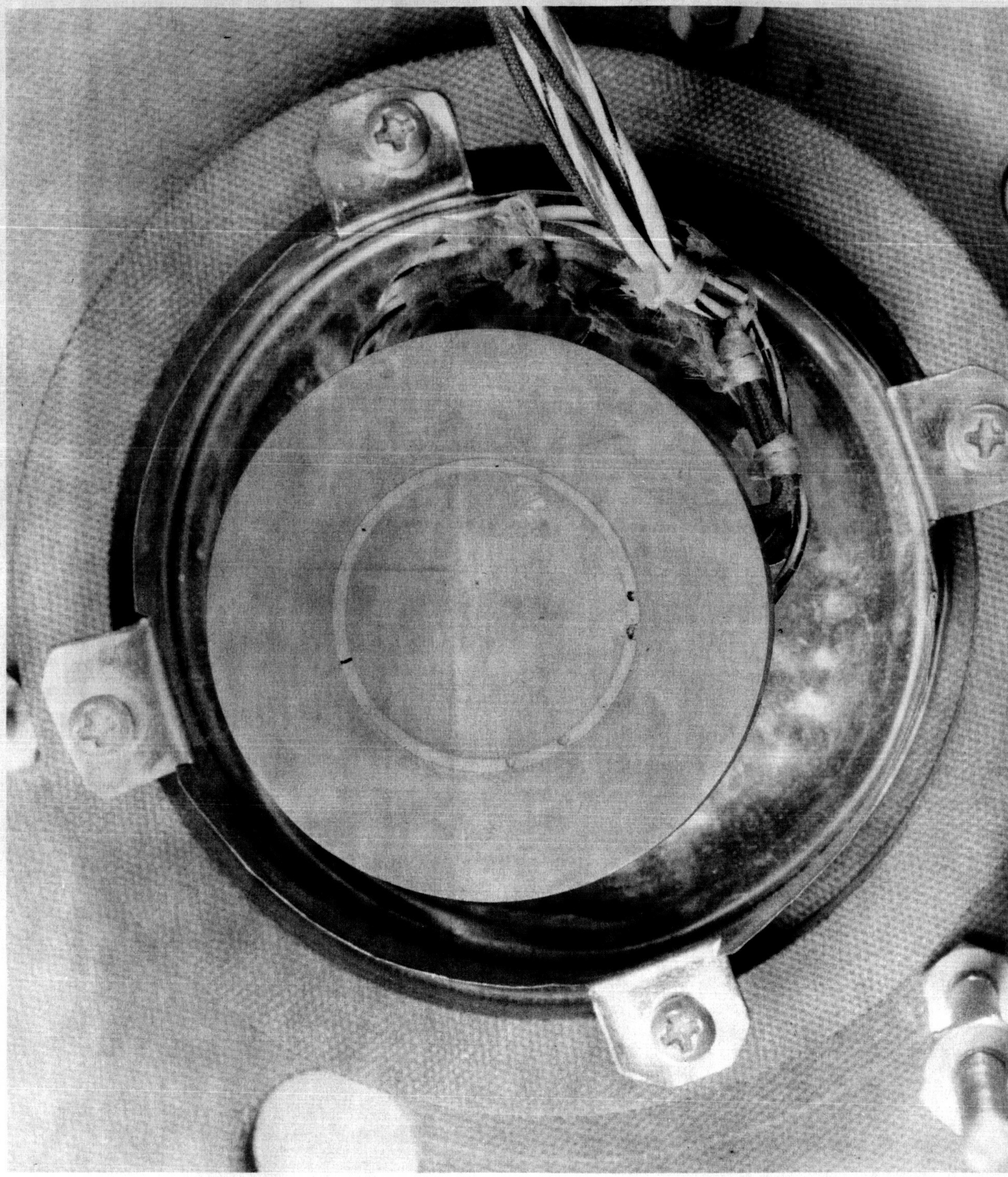
WARM PLATE IMPINGEMENT ASSEMBLY

Figure 2



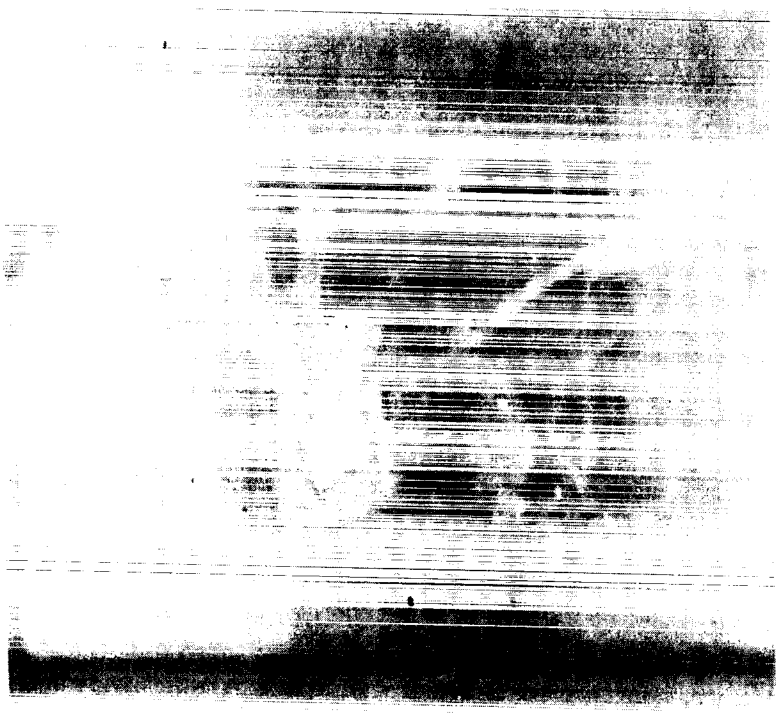
STAINLESS STEEL SPECIMEN

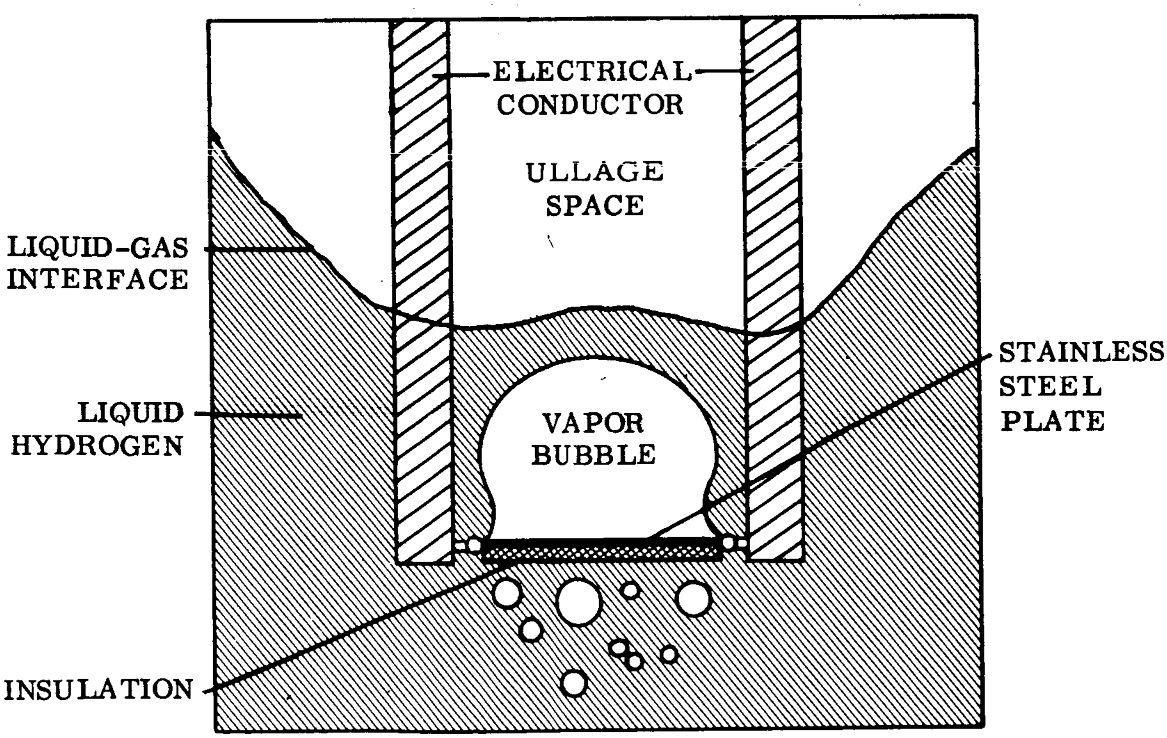
Figure 3



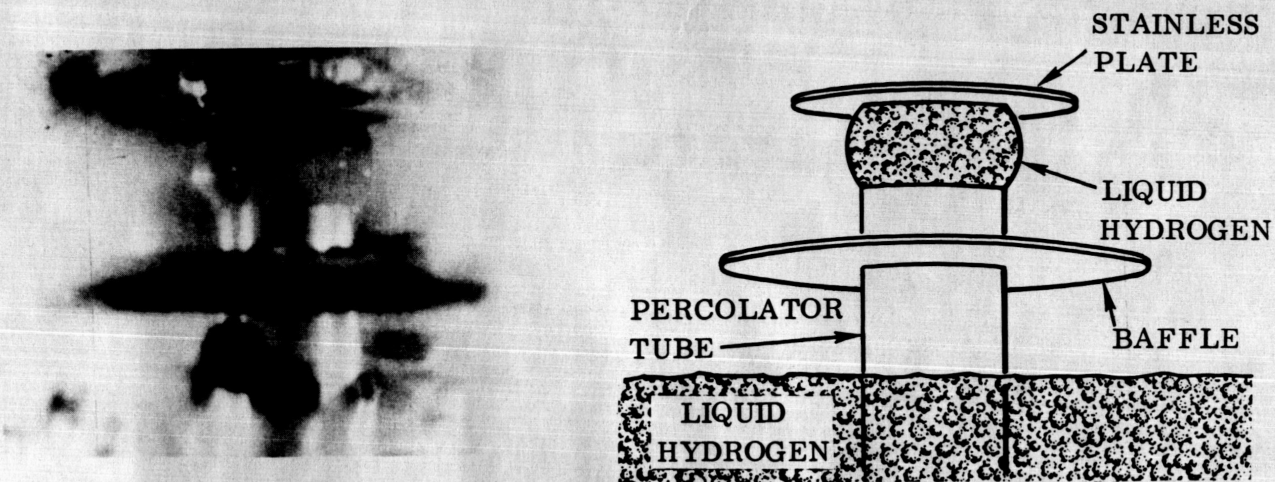
COPPER SPECIMEN

Figure 4

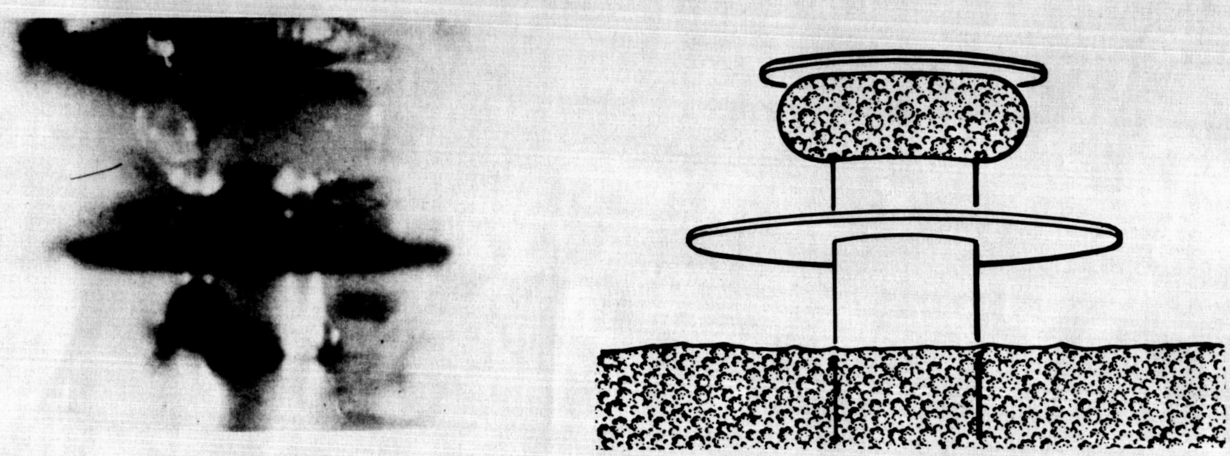




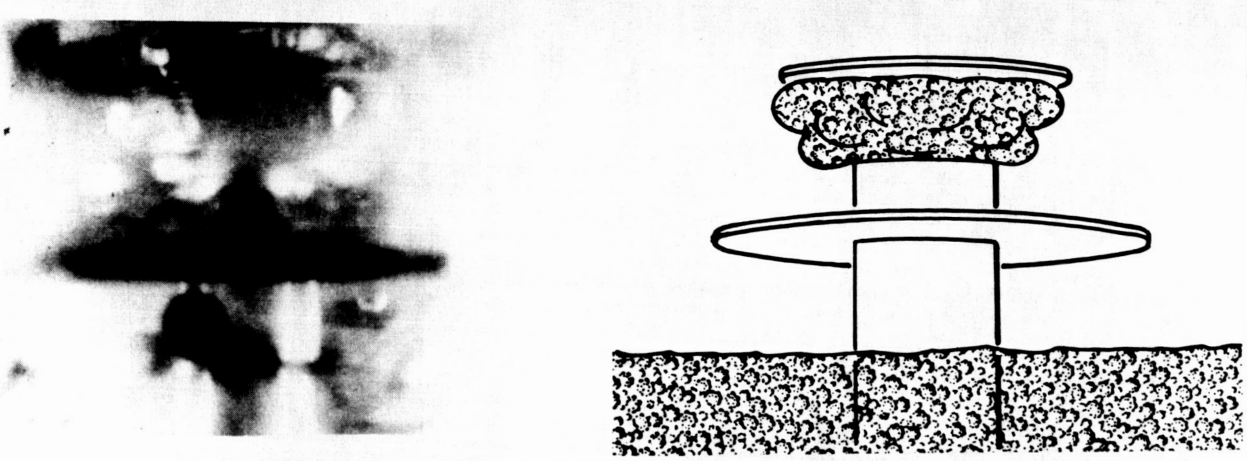
FILM BOILING BUBBLE FORMATION
DURING ZERO GRAVITY
FIGURE 5



1 SECOND AFTER CAPSULE RELEASE;
PLATE TEMP = 195° R, VELOCITY = 3.0 IN/SEC
A

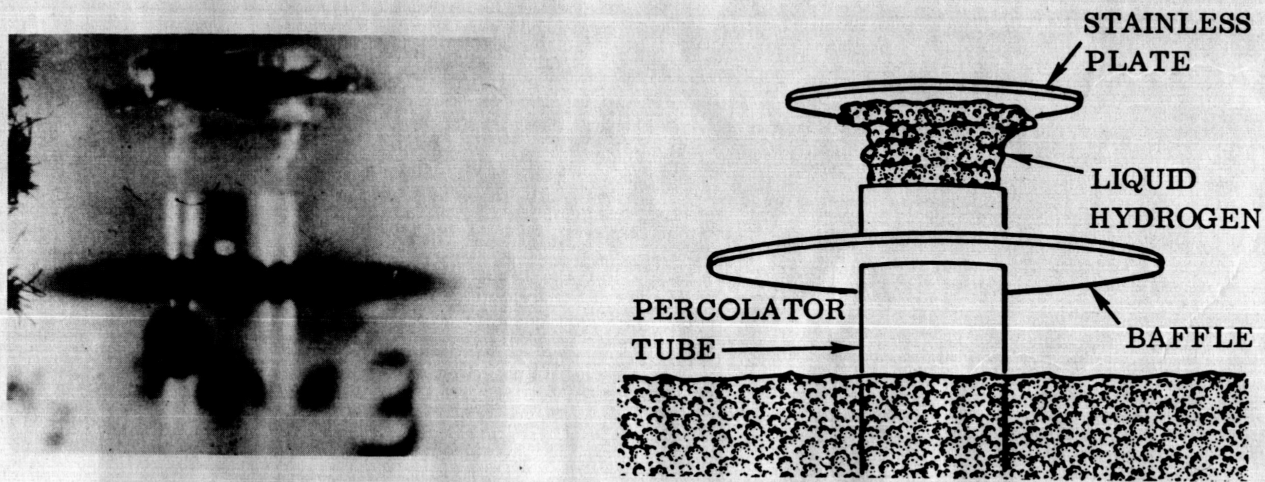


2 SECONDS AFTER CAPSULE RELEASE;
PLATE TEMP = 173° R, VELOCITY = 3.0 IN/SEC
B



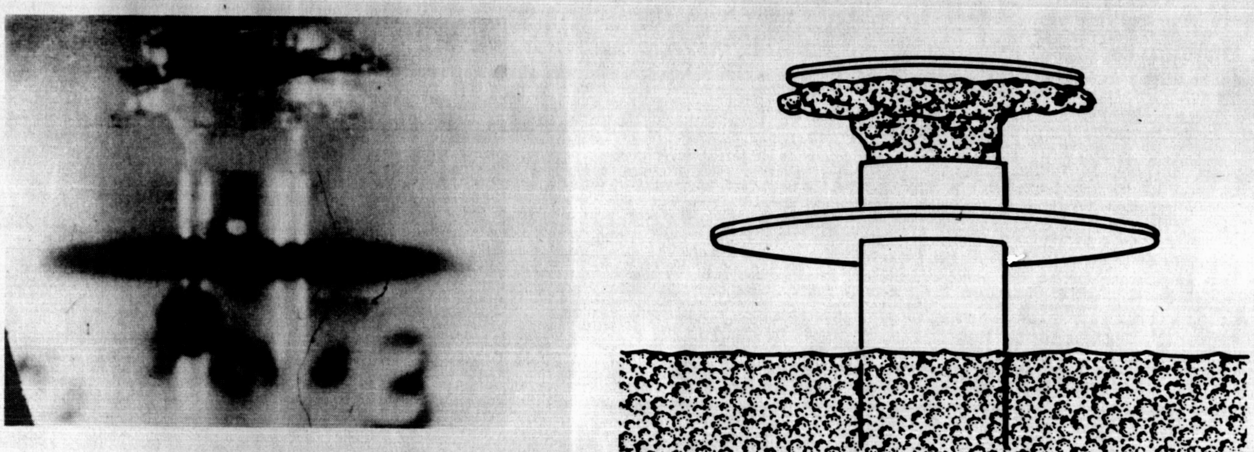
3 SECONDS AFTER CAPSULE RELEASE;
PLATE TEMP = 157° R, VELOCITY = 3.0 IN/SEC
C

FIGURE 6



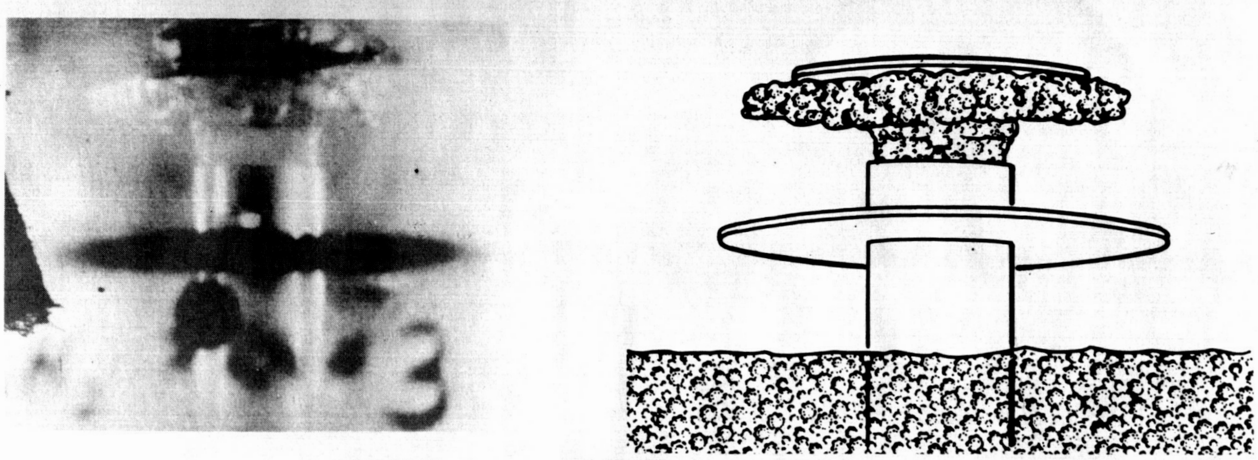
0.38 SECOND AFTER CAPSULE RELEASE;
PLATE TEMP = 288° R, VELOCITY = 5.0 IN/SEC

A



0.54 SECOND AFTER CAPSULE RELEASE;
PLATE TEMP = 283° R, VELOCITY = 5.0 IN/SEC

B



0.92 SECOND AFTER CAPSULE RELEASE;
PLATE TEMP = 279° R, VELOCITY = 5.0 IN/SEC

C

FIGURE 7

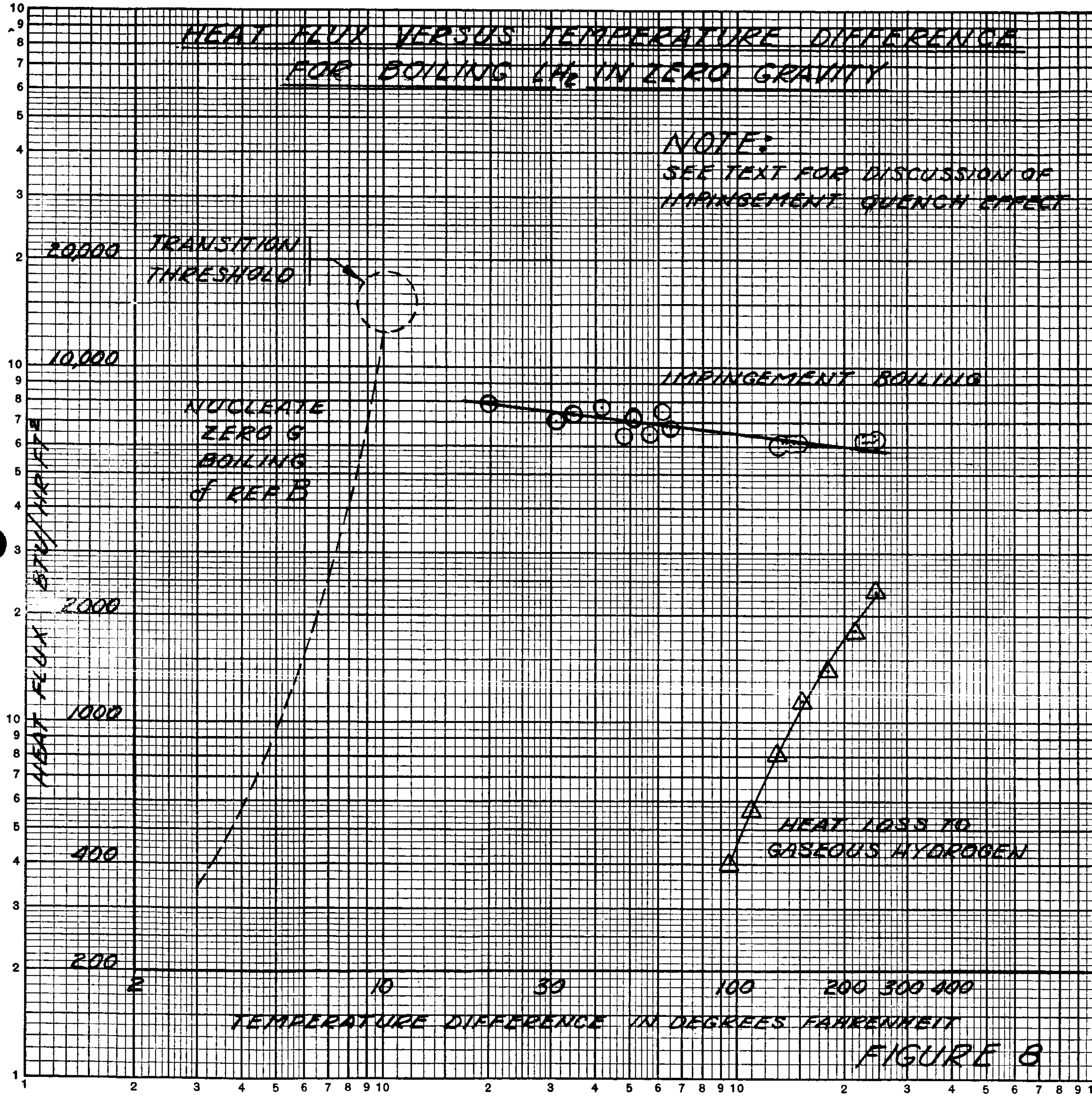

HEAT FLUX VERSUS TEMPERATURE DIFFERENCE
FOR BOILING LH_2 IN ZERO GRAVITY
NOTE:
SEE TEXT FOR DISCUSSION OF
IMPINGEMENT QUENCH EFFECT
TRANSITION
THRESHOLD
20,000
10,000
2000
1000
400
200
NUCLEATE
ZERO G
BOILING
of REF B
IMPINGEMENT BOILING
HEAT LOSS TO
GASEOUS HYDROGEN
HEAT FLUX BTU/HR FT²
2
10
30
100
200 300 400
TEMPERATURE DIFFERENCE IN DEGREES FAHRENHEIT

FIGURE 8

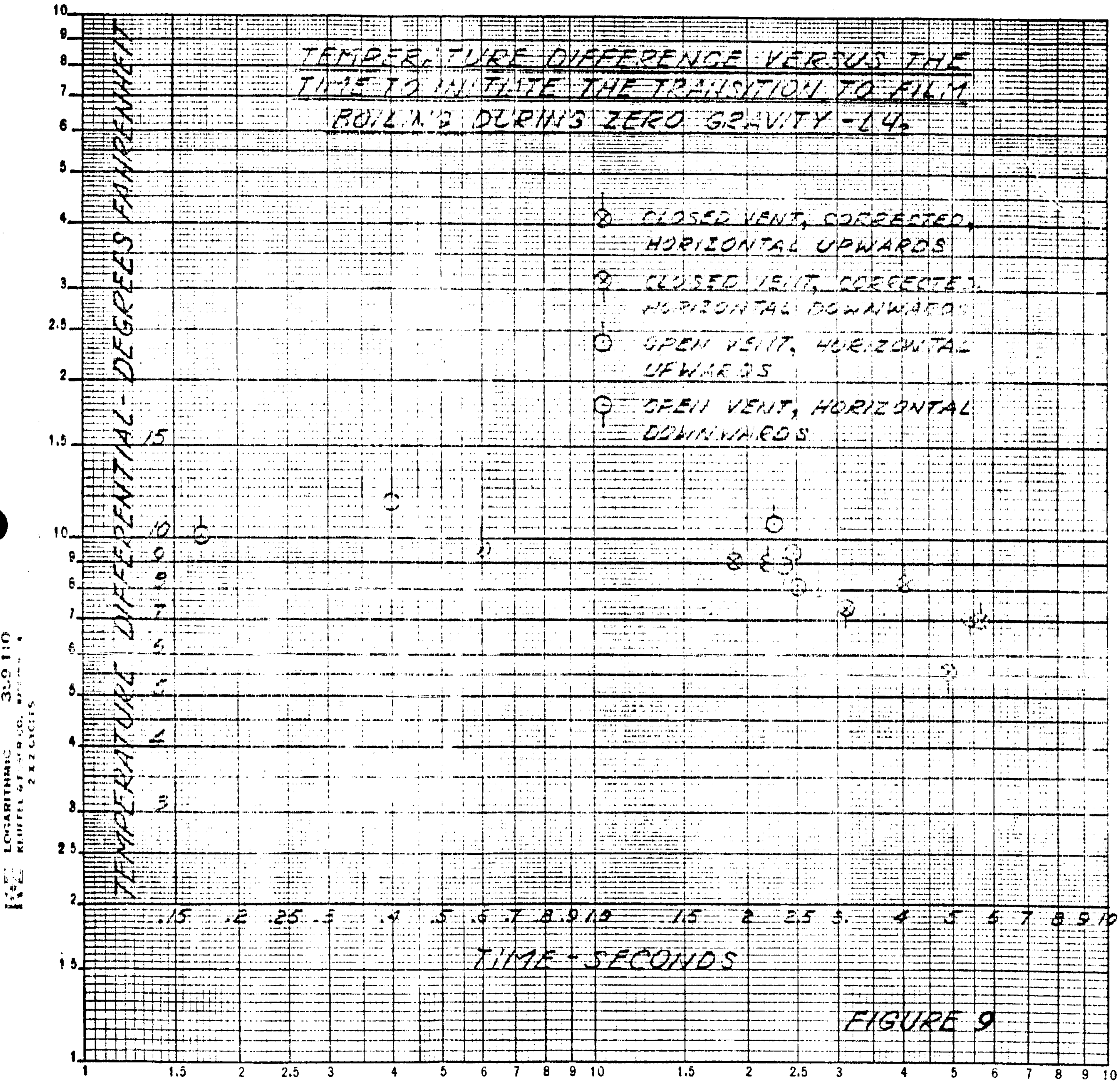

TEMPERATURE DIFFERENCE VERSUS THE
TIME TO INITIATE THE TRANSITION TO FILM
BOILING DURING ZERO GRAVITY - L4.
CLOSED VENT, CORRECTED,
HORIZONTAL UPWARDS
CLOSED VENT, CORRECTED,
HORIZONTAL DOWNWARDS
OPEN VENT, HORIZONTAL
UPWARDS
OPEN VENT, HORIZONTAL
DOWNWARDS
TEMPERATURE DIFFERENTIAL - DEGREES FAHRENHEIT
TIME - SECONDS

FIGURE 9

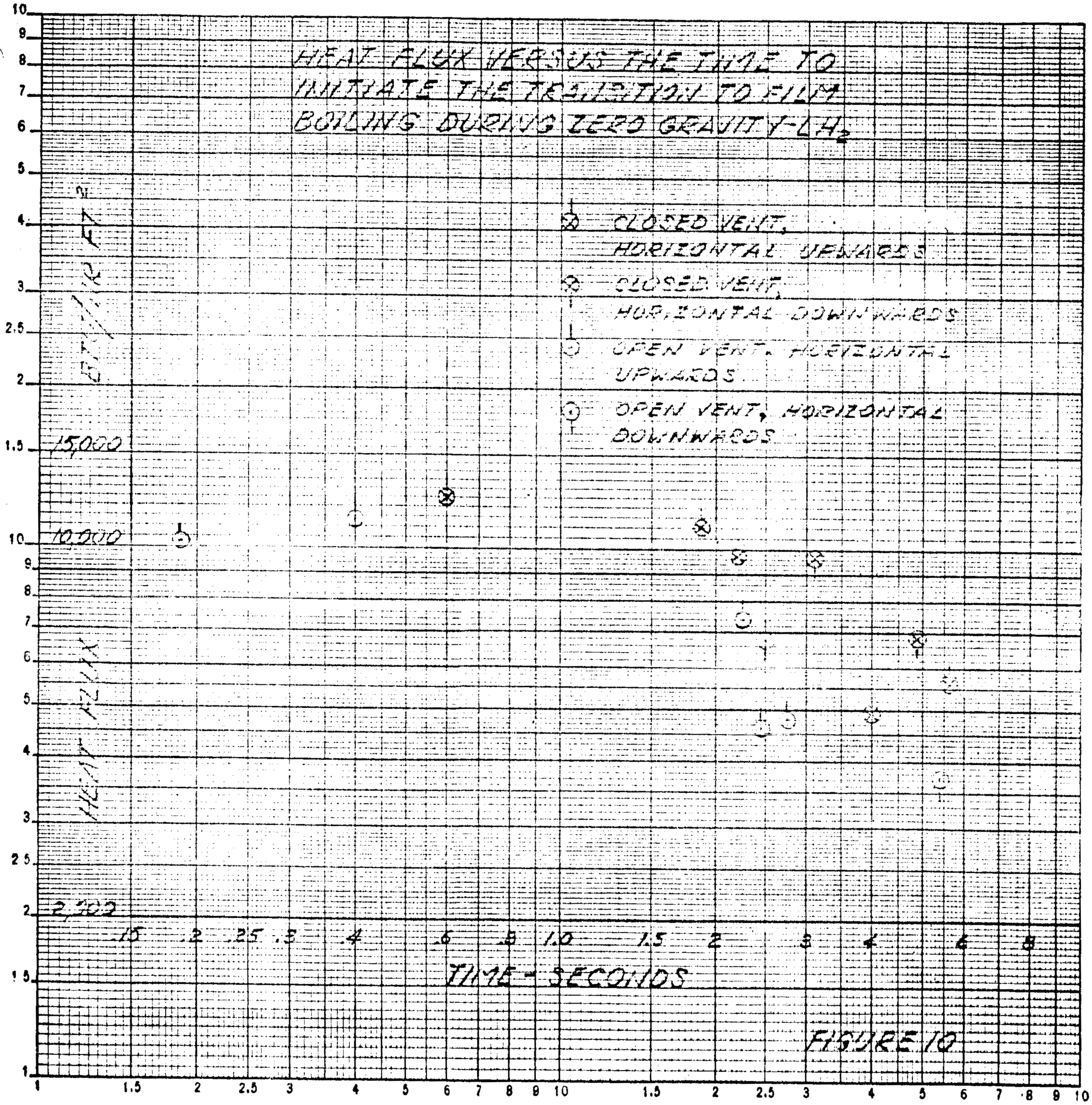

HEAT FLUX VERSUS THE TIME TO INITIATE THE TRANSITION TO FILM BOILING DURING ZERO GRAVITY-LH_2
CLOSED VENT, HORIZONTAL UPWARDS
CLOSED VENT, HORIZONTAL DOWNWARDS
OPEN VENT, HORIZONTAL UPWARDS
OPEN VENT, HORIZONTAL DOWNWARDS
HEAT FLUX BTU/HR FT^2
15,000
10,000
2,500
.15
.2
.25
.3
.4
.6
.8
1.0
1.5
2
3
4
6
8
TIME - SECONDS

FIGURE 10